

FAR INFRARED PHOTOVOLTAGE EFFECT IN A BLOCKED IMPURITY BAND PHOTODETECTOR

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ABSTRACT

A short circuit photocurrent is measured across a silicon blocked impurity band (BIB) detector when the device is illuminated at low temperatures with photons of wavelength up to about 30 μm . The photocurrent changes linearly with photon flux over a wide range of flux intensity while the open loop photovoltage remains surprisingly constant. The device is boron doped in its ohmic contacts and photoactive layer. The short-circuit photocurrent is shown to originate from photoemission of holes at the front contact with the pure blocking layer. The photoholes are ballistically transported across this micrometer thick pure layer.

INTRODUCTION

We report a far infrared (FIR) photovoltage effect which is unexpected in a silicon boron doped photoconductive structure having state of the art ohmic contacts. The structure includes between semitransparent highly doped contacts a 3 μm thick undoped layer next to a 6 μm thick photoactive layer doped with 10^{18} cm^{-3} boron impurities forming an impurity band. The front semitransparent thin contact with the pure layer is degenerately doped with 10^{19} cm^{-3} impurities. The device is fully described in Ref.2. A short-circuit photocurrent is measured at temperatures between 4 to 10K when illuminating infrared radiation power changes by several orders of magnitude down to a few $\mu\text{W}/\text{cm}^2$. The current varies linearly with the illumination intensity and flows always from the front contact towards the photo-active layer, independent of which contact is illuminated. The threshold wavelength of the photocurrent is found at the boron impurity photoionization ionization wavelength.

In this paper, we present a detailed study of the current-voltage photo-response of a BIB structure in the regime of small bias voltages, in contrast with the high bias operation of standard devices³. Our results present a new mechanism of the FIR photodetection.

EXPERIMENTAL RESULTS

Current-voltage (I - V) characteristics were measured at temperatures between 4 and -15 K, under illumination by a semiconductor $\text{Pb}_{1-x}\text{Sn}_x\text{Se}$ -laser emitting at 5.25 μm wavelength and delivering a controlled low flux level in the range $\Phi < 10^{14} \text{ cm}^{-2}\cdot\text{s}^{-1}$. A closed cryostat immersed in a liquid helium vessel was used to measure the photo-response at the low background with photon fluxes $< 10^{12} \text{ cm}^{-2}\cdot\text{s}^{-1}$. In

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addition, a standard optical cryostat was used in a Bruker IFS 113V Fourier spectrometer to illuminate the sample with a glowbar source at high flux levels $\Phi \sim 10^{16} \text{ cm}^{-2} \cdot \text{s}^{-1}$ and to measure the short-circuit current spectral response.

Fig 1 shows the I - V characteristics measured at 4.3 K under photon fluxes increasing successively by a factor of two from the base level $\sim 10^{14} \text{ ph/cm}^2 \cdot \text{s}^{-1}$.

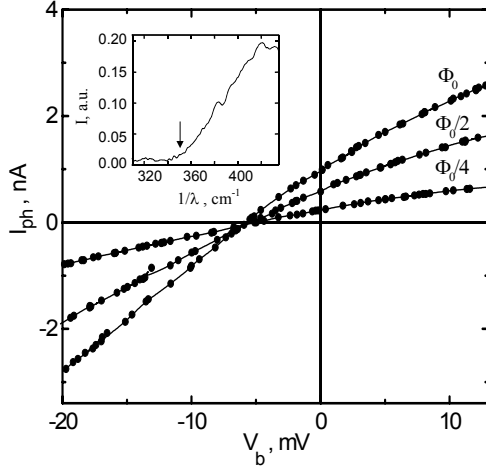


Fig.1. Current-voltage characteristics for Si:B BIB structures at $T=4.3\text{K}$ versus laser photon flux ($\Phi_0 \sim 10^{14} \text{ ph/cm}^2 \cdot \text{s}$). The insert shows the short-circuit photocurrent spectrum of at $T=6\text{K}$.

The key feature is the independence of the open-circuit photovoltage V_{emf} upon the intensity of the incident radiation while the short-circuit photocurrent behaves linearly. We were not able within experimental accuracy to reveal a photovoltage variation when decreasing the laser intensity by an order of magnitude. The open circuit photovoltage polarity indicates an internal electric field oriented towards the top contact. On the other hand, the short circuit photocurrent corresponds to holes flowing from the top contact past the pure layer towards the doped photoactive layer. The photovoltage polarity remained unchanged when the samples were back illuminated across the bottom contact, which excludes a photon-drag origin for the photovoltage. The insert in Fig.1 gives the onset of the spectral response measured on the short-circuit photocurrent. The threshold value at 350 cm^{-1} ($h\nu=43.4 \text{ meV}$) marked by an arrow coincides with the boron impurity ionization energy, $E_B=44.39 \text{ meV}$.⁴ Fig.2 displays I - V curves measured at several temperatures from 4 to 9.5 K at a flux level of $\Phi \sim 10^{14} \text{ ph/cm}^2 \cdot \text{s}^{-1}$. The photo-effect vanishes above

10K. Fig.3 shows in the same frame the temperature dependence of the photovoltage $V_{emf}(T)$ and the short-circuit current $I_{sc}(T)$. While the photovoltage decreases approximately linearly, the short-circuit current decreases slowly at temperatures $< 6\text{K}$ but then sharply above 7.5K. The symbols (\blacksquare) in Fig.3 represent open circuit photovoltage values for the room background radiation ($\Phi \sim 10^{16} \text{ ph/cm}^2 \cdot \text{s}$) at $T=6$ and 9 K.

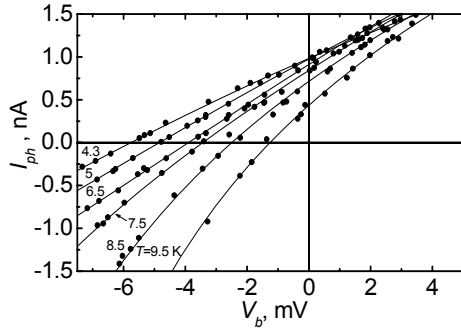


Fig.2. Current-voltage characteristics of Si:B BIB structures obtained at various temperatures under IR laser flux $\Phi_0 \sim 10^{14} \text{ ph/cm}^2 \cdot \text{s}$ at the wavelength $5.25 \mu\text{m}$.

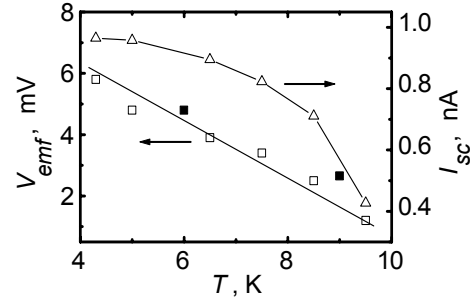


Fig.3. Absolute value of the short-circuit photocurrent I_{sc} (Δ) and photovoltage V_{emf} (\square) versus the temperature for Si:B BIB structure under a laser flux $\Phi_0 \sim 10^{14} \text{ ph/cm}^2 \cdot \text{s}$. (\blacksquare) - V_{emf} values under 300K background excitation.

DISCUSSION

Our discussion of hole photo-transport is based on the detailed energy band diagram of the Si:B structure at $T=0$ K and under zero bias as displayed in Fig.4. In this situation the Fermi level μ coincides with the ground state energy level of boron impurities in the pure layer. On the other hand in the impurity band of active layer, μ is positioned, according to reference [1], below the peak density of energy states,

located at the isolated boron energy level. The

energy difference $\Delta\mu = 0.99e^2 N_B^{1/3} / \kappa$, determined by Coulomb interaction, is equal to 12 meV in our case. An interesting consequence of the constant Fermi level is the formation of an energy barrier of height $\Delta\mu$ in the valence band. This barrier blocks the flow of holes into the pure layer excited in the active layer. Equivalently, the valence band structure barrier across the contact-pure interface is currently understood to arise from free holes and trapped holes on impurities on the pure layer.⁵ This barrier height is equal at $T=0$ K to the boron binding energy E_B . An important peculiarity of the pure layer is the long mean free path of free holes l_a limited at low temperatures by acoustic phonons scattering: $l_a \propto 1/T$.⁶ Using parameters of Si, we find for holes $l_a < 3 \mu\text{m}$ at $T < 6$ K. As a result, below 6 K, holes emitted from front contact and active layer cross ballistically the pure layer. Furthermore, in agreement with the data in Fig 3, the photocurrent is expected to decrease above 6K as the mean free path l_a becomes shorter than the pure layer thickness. In addition, the ballistic scenario is supported by the absence of this photo-effect in Si:Sb structures having 10 μm thick pure layer.

However, it is surprising to find the photocurrent flowing into but not out of the active layer, which means that the photo-emitted flow from the contact prevails over the active layer flow. This counter intuitive result calls for a detailed investigation of hole dynamics in front

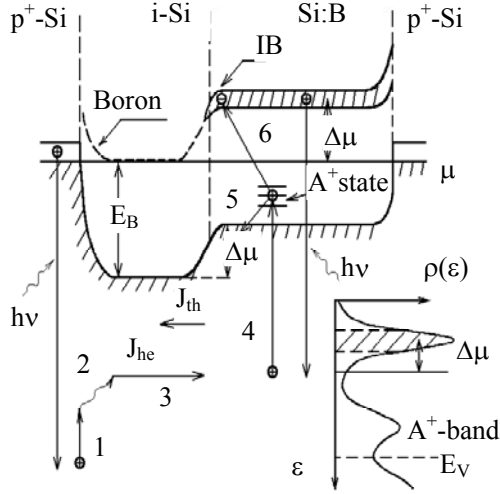


Fig.4. Energy band diagram of Si:B BIB structure. IB is the impurity band, μ is the Fermi level, E_v is top of the valence band, E_B is the ionization energy of the boron atoms in Si, $\Delta\mu$ is the Fermi level in the impurity band counted from the isolated boron ground state energy, $\rho(\epsilon)$ is the energy density of states. The arrows indicate relevant transitions involved in the photo-effect.

contact and active layer. Let us first consider in Fig.4 a hole just after absorbing a photon in the contact layer. Arrows 1,2 refer to the initial fast rate of the energy relaxation by optical phonon emission and to a more slower one by acoustic phonons, respectively. In doing so, those photo-holes have time to cross ballistically the pure layer as depicted by arrow 3. On the other hand, in the active layer when the kinetic energy of the photoexcited holes is below the optical phonon energy, a fast nonelastic hole trapping by neutral acceptors with emission of acoustic phonon takes place to form A^+ like states.⁶ The corresponding trapping time was calculated⁶ and measured⁷ in the case of Si with isolated neutral centers. Scaling results^{6,7} to our concentration gives τ_0 between 10^{-11} - 10^{-12} s that is less than the hole energy relaxation by acoustic phonons ($\tau_e \sim 10^{-10}$ s). Subsequently, after trapping, part of the trapped holes are thermally activated back into the valence band (arrow 5) while the rest recombines on the ionized acceptors (arrow 6). However, the thermally activated photo-holes are blocked by barrier height $\Delta\mu$ at the pure layer interface. Therefore, the net photocurrent flow originates from photoemission at the contact layer. Along this scheme, one easily explains the polarity of the open-circuit photovoltage as follows. Upon illumination, photo-emitted holes at the contact with the pure layer are transferred ballistically into the active layer until the photovoltage rises to balance the incident hole flow by a reverse flow of the thermally distributed holes in the active layer. Moreover, if the illumination intensity is increased the net balance of the opposite currents will be

maintained because each current increases proportionally with the illumination intensity. As a consequence, the open circuit photovoltage will not change.

At finite temperatures, the barrier height $\Delta\mu$ is reduced because the Fermi level will shift in the pure layer due to the compensation by donors. The barrier height becomes in the dark: $\phi = \Delta\mu - kT \times \ln[(N_B^* - N_D^*) / gN_D^*]$, where N_D^* is the donor concentration in the pure layer, g is the degeneracy factor of acceptors. Under illumination the photo-emitted current J_{he} from the contact turns out balanced by a thermoionic J_{th} current generated by the additional reduction of the interface barrier height by $\Delta\phi$. In the stationary regime the thermoionic currents: $J_{th} = J_0 \exp(-\phi / kT) [\exp(\Delta\phi / kT) - 1] = J_{he}$. Using this fact and taking into account that the open loop photovoltage V_{emf} equals $\Delta\phi/e$, we find:

$$eV_{emf} \approx \Delta\mu - kT \times \ln \left[\left(\frac{N_B^* - N_D^*}{gN_D^*} \right) \frac{J_0}{J_{he}} \right]. \quad (1)$$

Good agreement is obtained between the experimental V_{emf} data and the prediction of the expression (1). First, the photovoltage does not change with the illumination intensity since the ratio of currents is unchanged. Second, in the low temperature limit, the photovoltage varies quasi-linearly with temperature. It is noteworthy to point out that this dependence of the photovoltage extrapolates at $T=0$ K to 9.6 meV, slightly less than the theoretical Fermi level value $\Delta\mu=12$ meV.¹

It is interesting to estimate a responsivity R of our BIB detector in the short-circuit regime. According the data of Fig.1 the R value is about $3 \cdot 10^{-2}$ A/W at $\lambda \approx 5$ μm . The responsivity rises in the long-wave range of IR radiation as the absorption coefficient by free holes increases⁸. In particular, at the maximum of the short-circuit photocurrent spectrum ($\lambda \approx 24$ μm ; Fig.1) the absorption coefficient is expected⁸ 20 times higher.

CONCLUSION

A short circuit photocurrent is measured across a silicon blocked impurity band (BIB) detector when the device is illuminated at low temperatures with photons of wavelength up to about 30 μm . The effect is found in a structure having a pure layer thin enough to present ballistic transport of holes across this layer at low temperatures. The short circuit photocurrent proportional to the illumination level is produced by holes photo-emitted at the degenerate front contact layer. On the other hand, photogenerated holes in the active layer are blocked by a barrier at the interface with the pure layer. The photovoltage is constant. In the zero temperature limit it measures the interface barrier. The novel FIR photodetection presented above can be optimised to realize a useful device.

This work was supported by NATO (Grant PST.CLG.975592), RFBR (Grants 02-02-16974; 01-02-22004) and Region Midi Pyrénées.

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